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The ledge plant communities in a limestone cave of the Apuan area: identification and survey by UAV technology

Andrea Bertacchi[1], Diego Orazi[1], Leonardo Ercolini[1]

1 *Department of Agriculture, Food and Environment, University of Pisa, Via del Borghetto 80, 56124, Pisa, Italy*

Corresponding author: Andrea Bertacchi (andrea.bertacchi@unipi.it)

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Abstract

The Apuan Alps are a mountain range in the north-west of Tuscany, part of the Tuscan Sub-Apennines. The particular geomorphology, exposure, and biogeographic location create a diversified vegetation landscape across altitudinal and latitudinal gradients. The sclerophyllous formations of the Mediterranean scrub and woods of the maritime side coexist with mesophilous broadleaf woods and grasslands at higher elevations. In this context, it is possible to find heterotopic patches of evergreen sclerophyllous vegetation in the inner mountain complex, closely linked to the external walls of limestone reliefs. These sites, often characterized by superficial and deep karst phenomena, reveal the presence of underground cavities frequented by humans since the post-glacial period. This article presents a case study involving field surveys and UAV (Unmanned Aerial Vehicle) technology in a limestone cave near Tenerano (Massa-Carrara, Tuscany), to identify the species and the plant communities of the site for a historical reconstruction of the natural plant landscape.

Keywords

Apuan Alps, calcareous rocky slopes, chasmophytic flora, endemics species, *Quercus ilex*, vegetation

Introduction

The Apuan Alps are located in the northwestern part of Tuscany, where the transition between the continental European and the Mediterranean biogeographic regions is evident (Genovesi et al. 2014). The two regions are characterized by profoundly different vegetation landscapes. Briefly: the first region is characterized by forests of

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deciduous broadleaf trees in the basal layer and by conifers and other deciduous trees in the montane and alpine layer, both types of *Carpino-Fagetea sylvaticae* Jakucs ex Passarge 1968 and of the *Vaccinio-Piceetea* Br.-Bl. in Br.-Bl. et al. 1939. In contrast, the second region is characterized by plant communities of evergreen sclerophyllous forests and other thermophilous broadleaf trees in the basal layer of the *Quercetea ilicis* Br.-Bl. ex A. & O. Bolòs 1950 and forests of more mesophilous broadleaf trees in the montane layer always referred to the *Carpino-Fagetea* (Chytrý et al. 2024), In the Apuan area we find mixed vegetation aspects of these last two classes, influenced by geomorphological and altitudinal factors. Furthermore, despite having the same orogeny, the Apuan Alps are geologically isolated and detached from the Apennines. The tectonic evolution of the Apuan area has subsequently determined the uplift and exposure of a metamorphic complex constituted, at the base, by the formations of the "Autochthonous" Auct. (Carmignani et al. 2010). The particularly steep morphology, geographical position, and lithological heterogeneity are the main causes of these mountains' remarkable floristic and vegetational variety (ISPRA 2024+). The plant landscape is varied and composite: the sclerophyll formations of the Mediterranean scrub of the maritime side, rising in altitude, leave room for the woods mixed with *Ostrya carpinifolia* Scop., prevalent species, *Quercus pubescens* Willd. and *Quercus cerris* L. In this same low-mountain and medium-mountain belt, however, the artificial woods of *Castanea sativa* Mill. still prevail. The summit formations of casmophytic and glareic vegetation, emerge from the forests of *Fagus sylvatica* L., especially on the inner side of the chain, as well as primary and secondary grasslands with traces of suprasilvatic *Vaccinium myrtillus* groves (Ferrarini and Alessandrini 1988; Barbero and Bono 1973). The alternate glacial periods and climatic changes, the ancient anthropization, and the presence of karst areas and limestone external walls in this mountain complex have also determined the presence of heterotopic phytocoenoses of *Quercus ilex* L. in inner and higher parts of the chain (Arrigoni 1956; Barbero and Bono 1970; Ferrarini 1972).

These areas, often characterized by both superficial and deep karst phenomena, show underground cavities frequented by humans since the post-glacial period. As part of the PRIN project "Underlandscape" (2024+), a multidisciplinary investigation on the anthropic use and reuse of cave structures in the Apuan Alps, the botanical question was whether and how a diachronic reconstruction of the natural forest landscape surrounding the underground cavities was possible. Therefore, identifying the forest communities in their natural arrangement became crucial. After a preliminary inspection of several caves, it was found that only the plant communities that growing above the inaccessible rock walls could represent the natural vegetation.

The primary aim of the investigation was to quickly establish the main characteristics of the flora and vegetation of the Tecchia, or rather of its portions untouched by man, for a historical reconstruction of the natural plant landscape. Due to the extreme difficulty, if not impossibility, of conducting surveys on these rock ledges and external walls, UAV technology was used to identify the botanical species and the rock plant communities in a selected cave on the northern slope of the Apuan Alps.

Materials and methods

Study area description

The study was carried out in the Apuan cave near the village of Tenerano (Massa-Carrara, Tuscany, Italy), locally called "Tecchia di Tenerano" (WGS84: 44.1406°N, 10.1060°E; 481 m a.s.l.) (Fig. 1).

This is a particular geotope consisting of a high wall of cavernous limestone with, at the base, a large cavity approximately 150 m deep. The rock face, with a maximum height of about 75 m above the vertical of the spit, has a 90° slope and a southern exposure (Fig. 2). The cave is part of a larger karst system that develops in the basal carbonatic breccia of the Falda Toscana, emerging in the northern sector of the Apuan Alps and overhanging the metamorphic soils of the Apuan core of this Apuan sector (Openspeleo 2024+). While the surrounding forest landscape is characterized by old almost monophytic coppices of *Ostrya carpinifolia* and sparse chestnut groves of *Castanea sativa* (clear of anthropogenic origin), the walls and the top of the rocky buttress are characterized by the presence and dominance of *Quercus ilex*.

According to weather data recorded between 2014 and 2023 at the Equi Terme (Massa-Carrara) station, the average annual temperature is between 4 °C and 22 °C. Annual rainfall is approximately 1600 mm, with a maximum in autumn/winter and a minimum in summer (https://www.sir.toscana.it/consistenza-rete, 2024+).

Data collection

In June 2024 a field exploration was carried out to identify the species and phytocoenoses of the rocky complex. Given the morphological structure of the cliff, which prevented any access to the wall and the summit, it was necessary to use drone footage as an additional tool. This approach has proven useful in environmental contexts (wetlands, rocky coasts, cliffs, fire-affected environments) characterized by low accessibility (Bertacchi et al. 2019; Zhou et al. 2021; Bertacchi 2022; Porrovecchio et al. 2024). At the same time, the dense foliage of the underlying deciduous forest prevented the drone from taking off. For this reason, the drone footage was collected in autumn 2024. In both seasons, images were also taken from the ground using a reflex camera equipped with a 200× telephoto lens. Drone flight collected 15 nadir images and 10 front images were collected from a height of 10 m above the top and 10 m from the external wall face. This was done to obtain an orthophotogrammetric set useful for the 3D reconstruction of the rock complex. We used a DJI Mini 3 Pro quadcopter, equipped with its DJI-RGB camera (visible spectral range), lens FOV 82° 8.8 mm (format 24 mm equivalent), sensor CMOS 1/1.3"for 48 Mb per frame, and aspect ratio 8064 × 6048 pix. The flight was performed manually in just one time at speed of 1.5 m/s, with a medium overlap of 60% and a GSD (ground sampling distance) of 0.7 cm/pix. The 3D reconstruction was made using Metashape software (2024 © Agisoft).

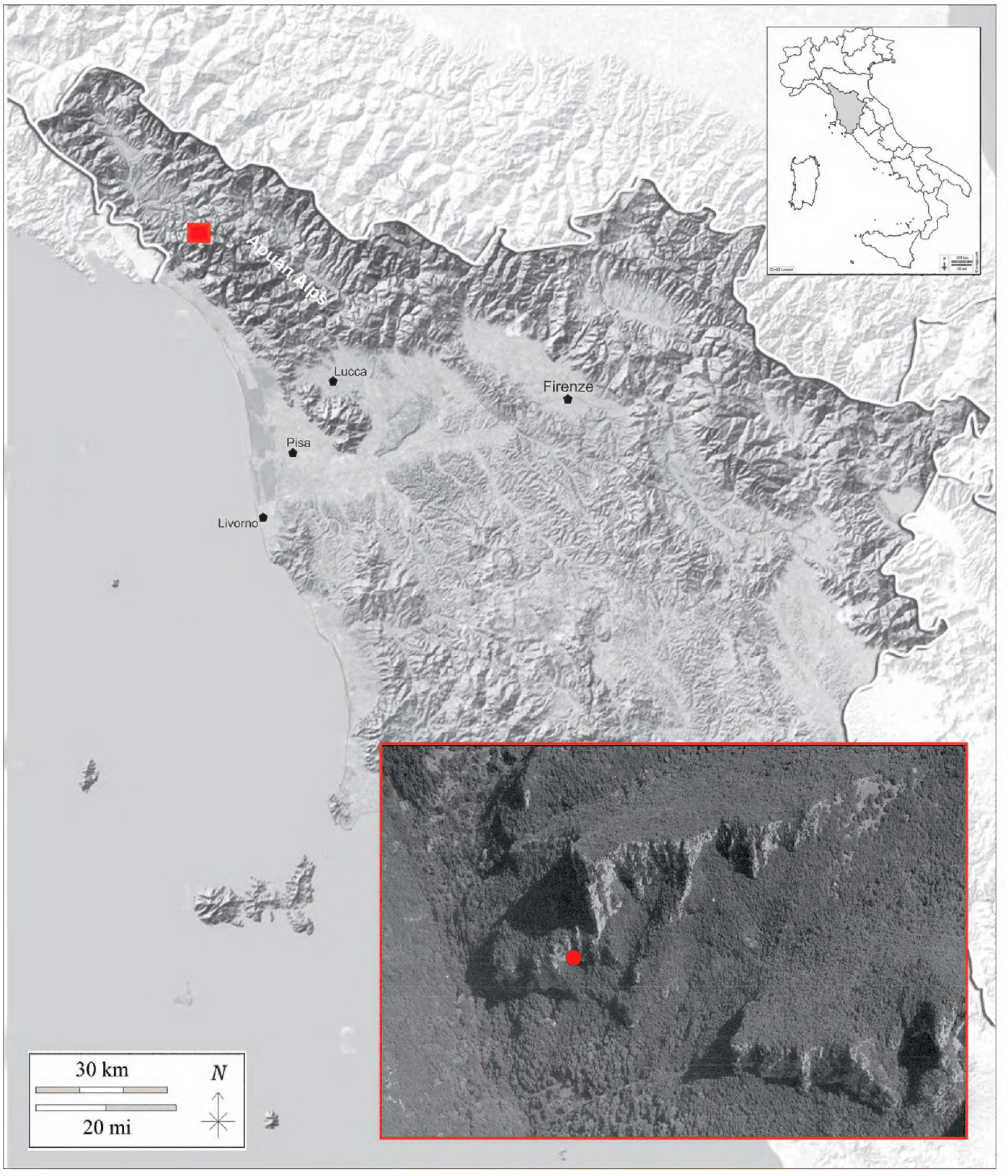

Figure 1. Geographical localization of study area; site of the cave (red dot).

Once the 3D model and the orthophoto were reconstructed, 5 areas of 60 m^2 were drawn to create the survey plots for vegetational relevé (Fig. 3). These were divided into quadrants of 1 m on each side in order to have an accurate measurement of the actual percentage cover. The Fig. 4 shows an example of the magnification of a survey plot (n°2).

Biological forms and chorology follow Pignatti et al. (2017–2019). Nomenclature follows Bartolucci et al. (2024) and their periodic updates in the Portal to the Flora of Italy (2024+; Martellos et al. 2024).

The plants coverage data are compared with a multivariate analysis (PCA), using PAST 4.03 software.

Figure 2. The cave and rock of "Tecchia di Tenerano".

Results and discussion

The exploration of the Tecchia portions untouched by man through drone footage and reflex camera shots, allowed us to identify 44 species and subspecies (Table 1). Although this detection technique does not allow sample collection and their definitive identification, the resolution is sufficient to permit specific attribution with a good degree of reliability (See Suppl. material 1). Sixteen of these taxa were also included within the drone footage plots, the remaining were shot or found outside the plots. The identified species are trictly linked to the rocky context and external to the cave.

Florula

The floristic list predominates arboreal/shrubby species (P+NP+Ch) on the H and G Life forms. (Table 1). From the drone footage on the limestone wall, no therophytes were identified. A predominance of Mediterranean chorotype and related subtypes (Fig. 5) was detected, and five italian endemics (*Atadinus glaucophyllus*, *Globularia incanescens*, *Moltkia suffruticosa* subsp. *bigazziana*, *Salix crataegifolia*, *Siler montanum* Crantz subsp. *apuanum* F.Conti & Bartolucci) were notable (Ansaldi et al. 1994; Roma-Marzio et al. 2015a, 2015b; Conti et al. 2021; Pierini and Peruzzi 2025).

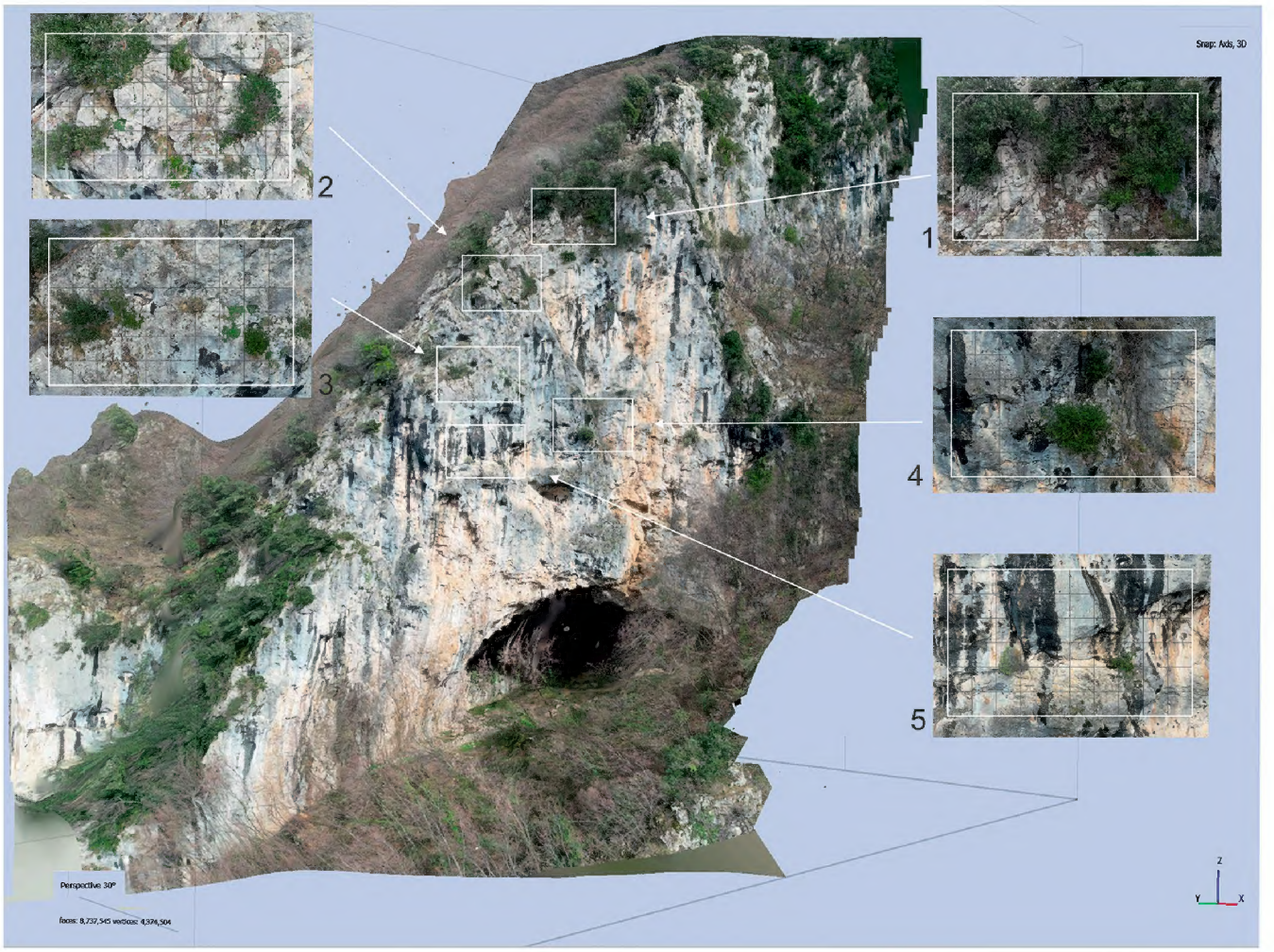

Figure 3. Sampling plots on the ledges of the external vertical wall of the cave reconstructed in 3D (Total area of the vertical cliff: 3630 m^2; the plot images are reported in full and with legend in Suppl. material 2).

Figure 4. Example of survey from footage sampling plot : Qi = *Quercus ilex*; Bg = *Brachypodium genuense*; Ag = *Atadinus glaucophyllus*; Au = *Arbutus unedo* Fo = *Fraxinus ornus*; Oc = *Ostrya carpinifolia*; Jp = *Juniperus phoenicia*; Ms = *Moltkia suffruticosa* subsp. *bigazziana*.

Table 1. List of the species identified on the rocky context and external to the cave.

Taxon	Choro	Lf
Lycopodiophyta and Polypodiophyta		
Aspleniaceae		
Asplenium ceterach L. subsp. *ceterach*	Eurasian	H
Asplenium trichomanes L. subsp. *trichomanes*	Cosmop.	H
Pteridaceae		
Adiantum capillus-veneris L.	Subtrop.	G
Eudicots		
Apiaceae		
Siler montanum Crantz subsp. *apuanum* F.Conti & Bartolucci	Endem. Ital.	H
Aquifoliaceae		
Ilex aquifolium L.	Subatl.	P
Araliaceae		
Hedera helix L. subsp. *helix*	Subatl.	P lian
Asteraceae		
Dittrichia viscosa (L.) Greuter subsp. *viscosa*	Euri - Medit.	H
Helichrysum italicum (Roth) G.Don	S-Europ.	Ch
Betulaceae		
Ostrya carpinifolia Scop.	Circumbor.	P
Boraginaceae		
Moltkia suffruticosa (L.) Brand subsp. *bigazzian*a Peruzzi & Soldano	Endem. Ital.	Ch
Caryophyllaceae		
Moehringia muscosa L.	Orof. Centroeurop.	H
Saponaria ocymoides L. subsp. *ocymoides*	Orof. SW-Europ.	H
Cupressaceae		
Juniperus communis L.	Circumbor.	NP
Juniperus phoenicea L.	Euri-Medit.	P
Dioscoreaceae		
Dioscorea communis (L.) Caddick & Wilkin	Euri-Medit.	G
Ericaceae		
Arbutus unedo L.	Steno-Medit.	P
Erica arborea L.	Medit.-Atl. (Steno)	P
Euphorbiaceae		
Euphorbia characias L.	Steno-Medit.	NP
Fabaceae		
Emerus major Mill. subsp. *major*	Centroeurop.	NP
Spartium junceum L.	Euri-Medit.	P
Fagaceae		
Quercus ilex L.	Steno-Medit.	P
Quercus pubescens Willd. subsp. *pubescens*	Europ.-Caucas	P
Lamiaceae		
Melittis melissophyllum L. subsp. *melissophyllum*	Centroeurop.	H
Teucrium chamaedrys L.	Euri-Medit.	Ch
Myrtaceae		
Myrtus communis L.	Steno-Medit.	P
Moraceae		
Ficus carica L.	Medit.-Turan.	P
Oleaceae		
Fraxinus ornus L. subsp. *ornus*	Europ.-Caucas.	P

Taxon	Choro	Lf
Primulaceae		
Cyclamen hederifolium Aiton subsp. *hederifolium*	N-Medit.	G
Rhamnaceae		
Atadinus glaucophyllus (Sommier) Hauenschild	Endem. Ital.	NP
Rosaceae		
Amelanchier ovalis Medik. subsp. *ovalis*	Medit.-Mont.	P
Rubus ulmifolius Schott *	Euri-Medit.	P
Rubiaceae		
Rubia peregrina L.	Medit.Macarones.	Pl
Salicaceae		
Salix crataegifolia Bertol.	Endem. Ital.	P
Sapindaceae		
Acer pseudoplatanus L.	Europ.-Caucas.	P
Smilacaceae		
Smilax aspera L.	Paleosubtrop.	G
Urticaceae		
Parietaria officinalis L.	Medit.-Turan.	H
Valerianaceae		
Centranthus ruber (L.) DC	Steno-Medit.	Ch
Monocots		
Asparagaceae		
Asparagus acutifolius L.	Euri-Medit.	G
Ruscus aculeatus L.	Euri-Medit.	Ch
Asphodelaceae		
Asphodelus ramosus L.subsp. *ramosus*	Steno-Medit.	G
Plantaginaceae		
Globularia incanescens Viv.	Endem. Ital.	H
Poaceae		
Brachypodium genuense (DC.) Roem	Paleotemp.	H
Poa bulbosa L.	Paleotemp.	H
Melica uniflora Retz.	Paleotemp	H

The predominance of the phanerophyte/nanophanerophyte/camephyte group can be explained by the ability of these species to quickly colonize the karst cracks in the rock with their root system, despite the substantial lack of soil. The absence of therophytes can in turn be interpreted on the one hand by the technical difficulty of identifying plants of small size, on the other by the difficulty of dissemination and establishment of therophytes on rocky substrates (Pichi Sermolli 1948; Arrigoni 1956). The rocky outcrop shows significant colonization of *Quercus ilex*, *Ostrya carpinifolia*, *Arbutus unedo* and *Fraxinus ornus* L., mainly at the top of the rock, along its ridge, and on the ledges of the vertical wall. Where the wall assumes significant slope values, other tree/shrub species such as *Atadinus glaucophyllus*, *Juniperus phoenicea* and *Moltkia suffruticosa* subsp. *bigazziana* become prevalent. Among these, *A. glaucophyllus* is largely widespread on the rock face. Occasionally *Amelanchier ovalis*, *Ruscus aculeatus* and *Asparagus acutifolius*, *Myrtus communis* are present. Among the herbaceous species,

Figure 5. Chorology and Life Form diagrams of detected flora of the study site.

common ones include *Brachypodium genuense*, *Parietaria officinalis*, *Centranthus ruber*. Species such as *Moehringia muscosa* L. *Helichrysum italicum*, and *Siler montanum* subsp. *apuanum* are localized. Inside the cave, there is no vegetation except for a widespread algal covering on the walls.

The flora is composed of plants specialized for the rocky environment and species with remarkable adaptability. *Quercus ilex* remains abundant due to its hardiness, biological plasticity, and the exposure to the southern quadrants of the Tecchia. This exposure also favors the presence of *Juniperus phoenicia* as well as other Mediterranean species. The five endemic species are closely linked to the Apuan rocky environments.

Vegetation

The analysis of footage of the sampled areas revealed a good return of the presence/coverage of the species (Figs 1–5; Suppl. material 2). In Table 2, the coverage of all the plots is reported.

The five plots sampled revealed differentiated plant coverages depending on the morphology and slope of the rock. The number of ledges and their spacing, the presence of more or less deep cracks, and the dripping of water condition the development and spread of plant communities.

The PCA analysis divides two different vegetation typologies: the communities of ledges, mainly arboreal/shrub and with a predominance of *Quercus ilex*, and the rocky slope wall communities, where only the more rustic species of small size can survive and constant presence of *Atadinus glaucophyllus* (Fig. 6). The scarcity of surveys and the impossibility of identifying species below a certain size (e.g. terophytes) prevent the attribution to phytosociological syntaxa. Based on prevalent and typical species, can still be distinguished the habitat 9340 - *Quercus ilex* and *Quercus rotundifolia* forests (92/43/EEC Directive habitats), whereas for some relevés, the recorded phytocoenoses may be associated with those included in habitat 8210 - Calcareous rocky slopes with chasmophytic vegetation.

Table 2. Vegetational surveys of the study site (species coverage in % of total area).

Plot n°	1	2	3	4	5
Altitude (m)	556	538	525	515	510
Area (m^2)	60	60	60	60	60
Total cover (%)	54.7	37.2	30.9	25.9	11.5
Quercus ilex	36.6	25.0	5.0	7.5	1.6
Fraxinus ornus subsp. *ornus*	1.6	0.8	0.8	–	–
Ostrya carpinifolia	5.8	1.6	1.6	–	–
Arbutus unedo	3.3	1.6	0.8	–	–
Atadinus glaucophyllus	0.8	0.8	11.6	11.6	5
Spartium junceum	–	–	–	1.6	–
Ficus carica	–	–	–	1.6	–
Juniperus phoenicea	–	1.6	–	–	3.3
Amelanchier ovalis	–	–	0.8	–	–
Moltkia suffruticosa subsp. *bigazziana*	–	0.8	8.3	0.8	1.6
Brachypodium genuense	6.6	5.0	1.6	0.8	–
Rubus ulmifolius	–	–	–	0.4	–
Asparagus acutifolius	–	–	0.4	0.4	–
Moehringia muscosa	–	–	–	0.4	0.4
Siler montanum subsp. *apuanum*	–	–	–	0.8	–

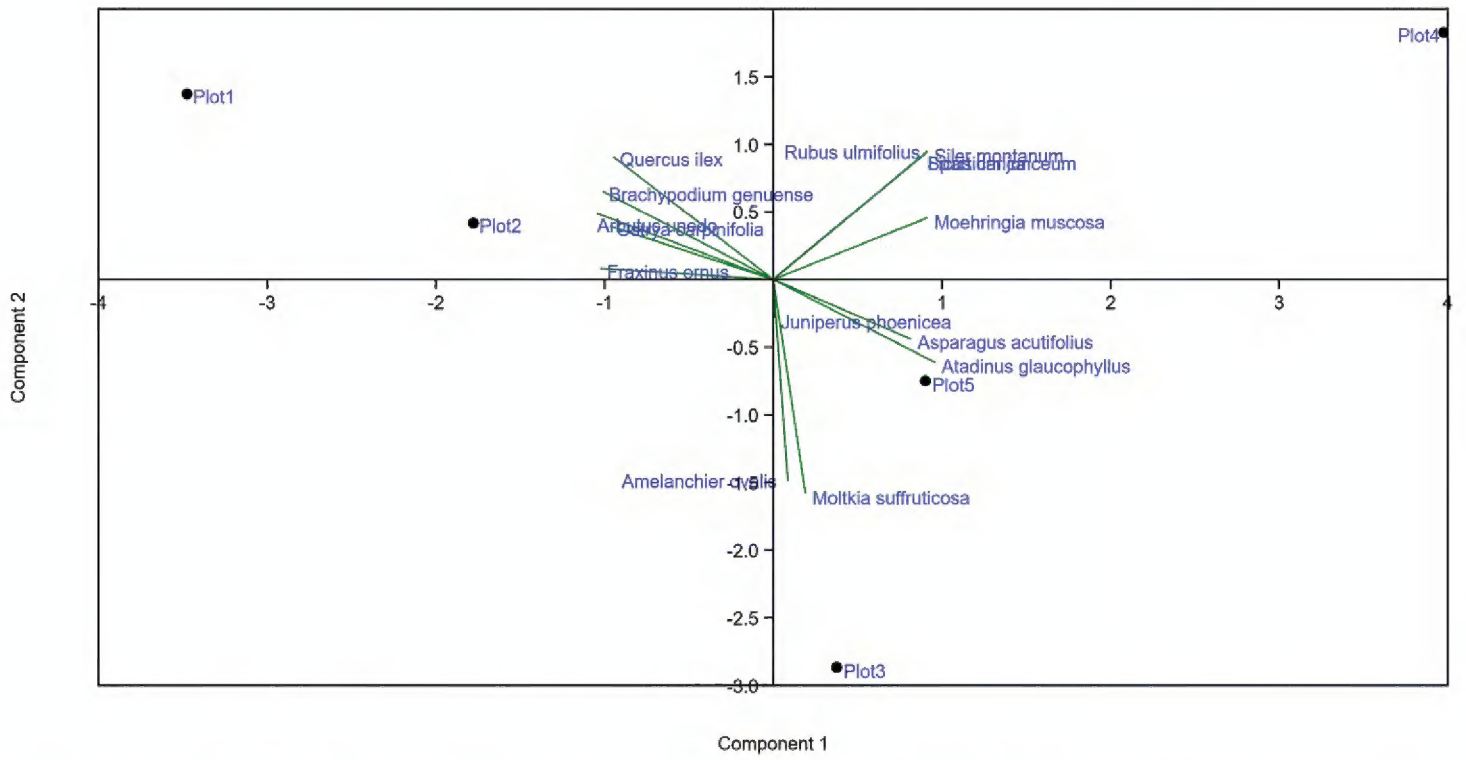

Figure 6. PCA of the five investigated plots (PC1 % Variance = 53.337; PC2 % variance = 23.639).

Although this detection system cannot be as comprehensive as the ground-based one, the combined use of drone images and high-magnification remote photography has proven essential for identifying species otherwise unreachable and hidden from view. Floristic studies in cliff environments have highlighted the extreme usefulness of UAV technology in floristic relief in inaccessible environments but still with a limit in the identification of smaller species (Strumia et al. 2020; Zhou et al. 2021; Seongjun et al. 2023). The floristic-vegetational traits of the investigated site are peculiar and

extremely interesting from a geobotanical, conservationist, and historical point of view. The particular conformation of the rock (geology, exposure, slope) determines the presence of distinctly Mediterranean species in a continental context which form communities with extrazonal vegetation characteristics. This have been documented for other similar environmental contexts in the Apuan Alps, where the populations of *Quercus ilex* in the "tecchie" have the character of extrazonal vegetation, with a distribution in the area strictly linked to these particular geotopes (Arrigoni et al. 1998).

These heterotopic stations are to be considered as relict rock-dwelling stations of post-glacial migrations of holm oak towards the interior of the Apuan territory during the anathermic period (Arrigoni 1956).

In these contexts, the holm oak, thanks to its hardiness and thermophilous nature, propagates and spreads in the crevices and ledges of the better-exposed "tecchie". Here it gives rise to xerophilous and thermophilous microcommunities where species characteristic of coastal scrublands such as *Fraxinus ornus*, *Smilax aspera*, and *Asparagus acutifolius* find a place. The investigated site supports endemic species strongly linked to the Apuan rocky environment (*Moltkia suffruticosa* subsp. *bigazziana*, *Atadinus glaucophyllus*, *Globularia incanescens*, *Salix crataegifolia*), within a completely different forest matrix.

The forest vegetation surrounding the cave and rock consists of hornbeam and oak-hornbeam woods and ancient coppiced chestnut groves, which have been historically managed for timber and fruit. While these plant communities align with the area's altitudinal and phytoclimatic characteristics, their physiognomy and species composition have been significantly altered over centuries of coppicing. Instead, the rocky plant communities, along with those more consistent with the vertical rock walls, can be considered as vegetation that has naturally evolved and never altered by human intervention. This vegetation provides a trace of the ancient plant landscape surrounding the caves.

All this makes the areas of the "Tecchia di Tenerano" of great interest not only from a geo-morphological, speleological, and historical-archaeological point of view but also from a naturalistic and conservationist perspective.

Conclusion

The survey highlighted the naturalistic importance of the site, due to its heterotopic nature and the presence of endemic species primarily associated with the Apuan chasmophytic environment. The use of UAV technology has proven valuable for identifying species that would otherwise be unidentifiable, although future advancements in sensor technology will enhance both resolution and identification capabilities.

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Supplementary material 1

A short photo collection of the identified species

Authors: Andrea Bertacchi

Data type: pdf

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Supplementary material 2

The five survey plots in detail

Authors: Andrea Bertacchi, Diego Orazi, Leonardo Ercolini

Data type: pdf

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